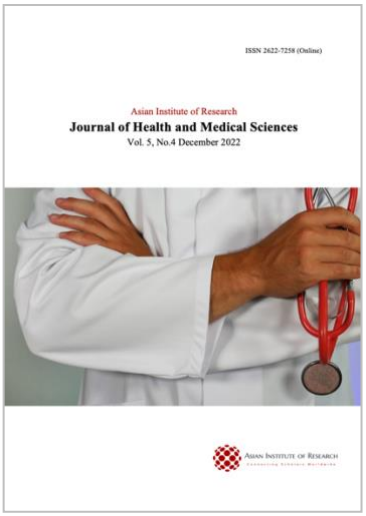

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Modelling an Extraterrestrial Epidemic

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Abstract
Panspermia is the theory that life has been transported between bodies in the solar system by means of asteroid or cometary impact. Assuming that panspermia is true, and that genetically related microbial life exists outside of our planet, then it is possible that such life could pose an infectious threat to the terrestrial biosphere. We offer several assumptions of the characteristics that such life might possess and extrapolate the likely epidemiological compartment approach to be applied when attempting to model the impact of an Earthly epidemic originating from an extraterrestrial pathogen.

Keywords: Panspermia, Epidemiology, Disease Modelling, Space, Exobiology, Astrobiology

1. Panspermia and the Cosmic Transit System

It is now an undeniable fact that terrestrial organisms can exist in both the lower and upper stratosphere (Griffin, 2004, Griffin, 2008, Shivaji et al., 2009, Smith et al., 2010, Yang et al., 2008, Yang et al., 2009). Strong evidence further supports the conclusion that multicellular organisms, like the tardigrade, can persist alive in the vacuum of interplanetary space (Rebecchi et al., 2009). In other words, the assumption that the existence of life is dependent upon conditions found on the habitable portions of Earth has been rendered incorrect by the identification of organisms capable of persisting in hostile, un-Earthlike environments. We call such organisms "extremophiles."

The existence of such extremophiles has brought back to mainstream discussion the fringe hypothesis of *panspermia*, which is the theory that life on this planet originated from microorganisms or chemical precursors of life present in outer space., While it is an idea originating in ancient times, panspermia has only known modern consideration since 1903, when Nobel prizewinning chemist Svante Arrhenius (Arrhenius, 1908) suggested that life on Earth might have originated from extraterrestrial sources. The original underlying thought was that interstellar material might have some organic component, which could have helped to seed life on this planet. The robustness of multicellular extremophiles has given some credence to the idea that the complexity of such cosmic organic material could be something grander than simple molecules, perhaps advancing to something resembling a single-celled organism.

Outer space is not the static, serene environment that many Earth-bound observers imagine it to be. Space is violent and full of collisions. Cometary and meteor impacts on one planet can rain down debris onto another planet (Donn,

1982). Indeed, much of the water in the inner solar system, including the Earth's oceans, might have resulted from repeated impacts with icy comets streaming in from the Oort cloud, or from impacts with ice meteors from the asteroid belt (Billings, 2014). Complex organic molecules aggregate on comets (Chang, 2015) and thus may also travel through the solar system on the cometary transit system. Cometary *panspermia* argues that comets are the carriers and distributors of cosmic life as well as the sites of replication of cosmic bacteria (Wickramasinghe, 2011).

The general *panspermia* theory came to global public prominence when the so-called "Allen Hills meteorite" (ALH84001), which was known from chemical analysis to have originated on Mars, and which likely was transferred to Earth via a violent meteor impact on Mars, showed signs of containing what some believed was a bacterial fossil (Thomas-Keprta et al., 2002). The rock was likely formed on the Martian surface some 4 billion years ago, and was ejected to Earth about 16 million years ago (Lapen et al., 2010). The ancientness of ALH84001 suggested that it would have left Mars when that planet was warmer and wetter, and therefore more welcoming to terrestrial norms of life. It also suggested that any Martian organisms alive on that rock might have either entered the terrestrial ecology or, more intriguing, might have ignited genesis on Earth.

Of the many arguments against the possibility of terrestrial life having originated off-world, one of the most compelling is that of Massimo Di Giulio (Di Giulio, 2010), who argued that since life on Earth went through many evolutionary stages, commencing with a protocellular stage, the initial off-world infection must have been protocellular, as well. A protocell is a collection of self-organized molecules, often lipids, proposed as a stepping stone to the origin of life. Yet experience with protocells suggests that they have extremely limited, if not null, infective power. A non-infective cell could not have triggered our Earthly genesis, as its ability to replicate, or to inspire the replication of others, is limited.

Despite such a rational argument to the contrary, mainstream acceptance of the panspermia hypothesis is growing. It is the core premise for several mass entertainment products, such as the 2000 motion picture, *Mission To Mars*. To some, the growing acceptance of panspermia represents a genuine research paradigm shift (Wickramasinghe and Trevors, 2013). It is nevertheless a dangerous idea, at least to the careers of its proponents. Its most vocal current champion, Sri Lankan astrobiologist Chandra Wickramasinghe, has provocatively suggested that common terrestrial lifeforms, such as the SARS virus and the alga spores present in the "red rain" of Kerala, India, are in fact alien species (Wickramasinghe et al., 2013), and has been derided for his beliefs by more traditional scientists (Lovgren, 2003).

Massimo Di Giulio's argument against panspermia assumes that in order for the panspermia theory to be valid, the organisms that would have traveled to Earth would have had to be complex in nature in order to survive, presumably because less complex progenotes (a hypothetical pre-life stage) would have likely liked the self-reparatory abilities necessary to endure the assaults of radiation and vacuum. While the extremophiles thus far identified that are able to persist in outer space are indeed complex, Di Giulio fails to consider the possibility of non-living genetic materials, and not organisms, traversing interplanetary space, perhaps in plain molecular form or wrapped in a very simple living organic package, such as a virus. In such a scenario, elements of extraterrestrial life could have contributed material to a nascent terrestrial ecology, rather than being its overt and sole source.

2. Panspermia and Disease

All proposed models of panspermia, from those positing off-world sources as the sole origin of Earthbound life to those allowing for a hybridization of geneses, necessarily suggest one implication, that life beyond Earth will be, in some ways at least, biologically similar to familiar terrestrial life. Therefore any alien lifeform arising from the same panspermic source will, to some degree, find purchase within our biosphere. And, conversely, a terrestrial organism would be able to interact with an alien ecology, perhaps even the digestion of alien foods or, in the case of single cell organisms, the incorporation of alien genetic material.

An obvious corollary to this realization is that biospheres originating from the same panspermic cosmic seed can not only exchange genetic material, but can be literally infected by each other's agents. Panspermia allows for the

existence of diseases from outer space, as Wickramasinghe creatively argued was the case for the SARS virus, and as aerospace student Ashley Dale suggested was the origins of Ebola:

> "There is always a chance the Ebola virus could have come from outside this planet at some point during the evolutionary process. We have meteorites from Mars landing on our planet every year, bacteria can survive this journey, we have already seen this in laboratory experiments simulating the extreme environment. Virus particles can also make it through undamaged so there is definitely a possibility something could have arrived back in the evolution of the planet that we are seeing now." (Young, 2014)

Similarly, astronomer Fred Hoyle had suggested that the 1918 Spanish influenza outbreak was the result of a virus that had fallen from space (Millar, 2000). Assuming that Wickramasinghe, Hoyle, and Dale are incorrect, and that all known diseases have banal terrestrial origins, then we have yet to experience a genuine alien epidemic. Should such a pathogen enter our biosphere, how would such an outbreak be modeled epidemiologically? How could we predict its spread and thus manage the outbreak from a public health standpoint?

We propose two possible types of alien infections: toxic and infectious. The former type can deleteriously affect a terrestrial lifeform upon contact. The latter can be transmitted between terrestrial lifeforms, thus creating an outbreak, a possible epidemic, or a possible pandemic. If infection by alien pathogens seems unlikely, given the vast evolutionary distance between organisms from different planets, consider the bacterium *Serratia marcescens*, which can pass from human beings to coral, despite the evolutionary distance between those two organisms. Infectious diseases are diabolical and adaptive monsters, often with a resourcefulness that stymies their multicellular victims and hosts.

The possibility of an infectious agent jumping from alien soil samples to the human biosphere has raised alarms in some sectors of the space science community. The International Committee Against Mars Sample Return (ICAMSR) has, since 2000, argued against any mission to the Red Planet which seeks to bring Martian material back to Earth, precisely to avoid the possibility of an alien epidemic.

ICAMSR's website implores us to consider the following passage from page 114 of Carl Sagan's 1973 book, *Carl Sagan's Cosmic Connection: An Extraterrestrial Perspective* (Sagan, 1973):

> "Precisely because Mars is an environment of great potential biological interest, it is possible that on Mars there are pathogens, organisms which, if transported to the terrestrial environment, might do enormous biological damage - a Martian plague, the twist in the plot of H. G. Wells' War of the Worlds, but in reverse. This is an extremely grave point. On the one hand, we can argue that Martian organisms cannot cause any serious problems to terrestrial organisms, because there has been no biological contact for 4.5 billion years between Martian and terrestrial organisms. On the other hand, we can argue equally well that terrestrial organisms have evolved no defenses against potential Martian pathogens, precisely because there has been no such contact for 4.5 billion years. The chance of such an infection may be very small, but the hazards, if it occurs, are certainly very high."

This is, of course, essentially the plot of the 1969 novel and 1971 film, *The Andromeda Strain*, in which a crashed satellite delivers to Earth micrometeoroid material that contains an alien pathogen, resulting in a fast spreading deadly epidemic.

Discussion of epidemics of alien diseases on Earth is, of course, the domain of extreme speculation and imagination. But it may not be the domain purely of science fiction, as it is seated in the facts of known science and delineated by the acknowledged limitations of life as we know it. Willerslev et al (Willerslev et al., 2003) argued that if an alien pathogen could enter our biosphere, it would imply three things. First, any extraterrestrial source of DNA must arise from ecological conditions similar to Earth. Second, that specialized pathogens must have extraterrestrial hosts similar to those of Earth. And third, that the extraterrestrial source must be close to Earth, to allow for minimal exposure of the genetic material to the hostile and denaturing forces of interplanetary space. Since we know of no planet, beyond the Earth itself, harbouring these conditions, the authors suggest that an alien disease is unlikely.

The arguments of Willerslev et al are diminished by at least two inconvenient truths. First, everything known about life is derived from a sample size of one: the Earth's biosphere. It may be foolhardy to impute universal rules about

cosmic organisms, such as their environmental limits, dimensions, robustness, and life cycles, from observing only the end product of billions of years of evolution on a single planet. Second, it must be acknowledged that organisms are not the only source of infections. We also must contend with strange infectious agents at the far horizon of what is considered life; things like prions.

Prions are small proteinaceous infectious disease-causing agents that are believed to be the smallest infectious particle They are neither bacterial nor fungal nor viral and contain no genetic material (Institute of Medicine Forum on Emerging, 2002). They can fold in multiple ways and can transmit their folding pattern to other proteins. Often, this infective behavior results in extreme fatality when the affected protein is in a living organism. Bovine Spongiform Encephalopathy (BSE), or "mad cow disease," and its human correlate, Creutzfeld-Jakob Disease (CJD) are terrifying incurable diseases caused by prions. Such proteins are technically not alive (though this depends upon one's definition of life), but they do evolve (Li et al., 2010). And, it should be noted, amino acids, which are the building blocks of proteins, and thus prions, have been found on comets (Atkinson, 2009). The possible arrival of an alien prion would violate no laws of biology or physics, nor would it conflict with anything that is known of terrestrial biology or organic chemistry.

Whether that epidemic is caused by a prion, a virus, a bacterium, or something more exotic, the increasing likelihood of a panspermic reality suggests that an Earthbound epidemic caused by an alien pathogen is worthy of epidemiologic and public health attention. Responding to such an epidemic requires epidemiologic modeling. But an alien disease poses some challenges to traditional modeling approaches. If such an epidemic were to befall us, it is advisable to know which of its characteristics are most critical to be studied, in order that useful modeling can be performed.

3. The Epidemiology of Aliens

The underlying assumption of our analysis is that the style of panspermia that would allow for alien diseases on Earth is that sibling biospheres would share a common genetic philosophy, meaning that an alien organism would also have at its cellular core a molecule coding for genetic information, an analogy for our DNA, if not actual DNA. Thus, the pathogen's mutation, like in Earthly cells, would be the reorganization of that genetic material in response to some environmental assault, most commonly solar or cosmic radiation.

3.1. Epidemiologic Modeling

Epidemiologists predict, manage, and help to control epidemics of terrestrial diseases by modeling their spread, thus enabling the marshalling of resources and the appropriate preparation of vulnerable populations. All models rely upon basic assumptions to define baseline parameters that allow for the projection of disease prevalence, incidence, and rate of spread. The utility of such models is obvious. They allow for such critical public health interventions as mass vaccination programs, or even help to determine whether extreme measures, such as mass quarantine, need to be implemented.

A variety of modeling approaches can be applied to infectious disease management, though we only consider the most basic examples for this analysis. For all models explored herein, we feel that four parameters are of particular relevance, and must be estimated: the basic reproductive number, which is the average number of cases that one case generates over the course of its infectious period; the proportion of the population who are susceptible to the disease; the average age at which the disease is contracted; and the average life expectancy of the population. Clearly, only the last parameter can be estimated or computed in absence of any knowledge of the disease. And none of these factors can be surmised about an alien infection without direct examination of a sample or of its observed effects on humans.

An additional assumption in all models considered in this paper is that the population's age distribution is stationary. In other words, in the absence of the disease, most people would live to that population's computed life expectancy, which is a valid assumption for most developed countries with low infant mortality. We also assume that the population mixes in a homogenous manner, with minimal clustering. Obviously, these two assumptions in no way reflect the reality of any known human population. In fact, as an epidemic progresses, the core

assumptions accelerate in their inapplicability as population age distributions become skewed, and as people change their travel and habitation behaviours in response to the threat of infection. So it must be remembered that disease models do not represent reality in all its nuances, but only to the extent that the models' behaviours provide useful insights for policy directives.

Stochastic epidemiologic models seek to estimate the probability distributions of selected disease outcomes, such as death, impairment, or recovery, as functions of various randomly (or pseudorandomly) fluctuating characteristics. A deterministic model, on the other hand, seeks to determine how portions of the population transition from one stage of the disease to the next. The most common of the deterministic models is the SIR model, which uses three compartments or stages: S ("susceptible") is the compartment of people not yet infected with the disease, or, more accurately, those capable of contracting the infection; I ("infected") is the compartment of individuals who have been infected and are capable of spreading it to others; and R ("recovered/removed") is the compartment of those who have been infected and then rendered unable to infect others or to become re-infected, either because of their deaths or immunization. In other words, S→ I → R.

The SIR model, then, uses a fixed population, wherein N = S(t)+I(t)+R(t). Derivatives of each function relative to time provide estimates of the change in the numbers in each compartment, and thus give us a fluid model of the flow of the epidemic from one compartment to the next.

A modification is the SIS model (S → I → S) in which those who recover from the disease are rendered susceptible yet again, as there is no acquired immunity. Another possibility for seriously infectious pathogens is the simple S → I model, in which susceptible individuals become both infected and infectious and remain so.

Some models include a fourth potential latency compartment, E, which describes those individuals who have been exposed to the disease, but are not yet ill, nor are they infectious. In other words, S → E → I → R. The E compartment does not include those that are asymptomatically infected. In reality, all infectious diseases have a latency period. But for some, its length is small enough to be mathematically negligible, at least to the extent that it has any meaningful effect on the larger model.

The utility of each model to an instance of an extraterrestrial infection depends upon the nature of that infection. The question now becomes, what are the critical characteristics of an unearthly pathogen that are essential to allow effective modeling?

3.2. Modeling an Alien Bug

In the event of an alien infection, the major mechanism of pathogenesis must be considered. Pathogenesis is distinct from infectivity inasmuch as the latter describes an agent's ability to infect, whereas the former describes its ability to cause disease. There are three possibilities: direct tissue invasion (much like many earthly parasites or fungi), immunologic enhancement or suppression (much like an allergy or even HIV), or toxin production (much like many bacterial diseases, such as botulism).

A handful of considerations must be acknowledged when embarking on a thought experiment to describe alien disease. First, it may be true that fundamental genetic incompatibility between Earthly and alien life might mean that our bodies would not recognize alien life as living, and vice versa; thus, an alien virus analog would be unable to use our DNA for self-replication. Second, due to such genetic incompatibility, it is possible that an Earthly host would not respond at all to an alien "infection." And third, a truly alien organism might be so physically incompatible with our bodies as to prevent it invading and infecting a human host. Despite these possibilities, we proceed under the assumption that *panspermia* implies a common biological heritage between terrestrial and alien life, thus allowing for physical and genetic compatibility necessary for infection.

To develop a model of an alien epidemic, the mode of disease transmission must be determined. On Earth, we often acquire infections through contact with an infectious person. Contact can be direct or indirect. HIV is transmitted through the most intimate of direct contact. Some infections can be acquired by touching a surface that was touched by a carrier. Or one can imbibe a droplet of fluid exhaled by a carrier, perhaps by inhalation or contact

with one's mucous membranes, which is how the common cold is spread. Non-contact methods of transmission include the vector-borne pathway, like that used by malaria, which uses the bite of a mosquito to spread itself.

In brief, modes of transmission can be either via contact or not requiring contact. Contact-based transmission is either by three avenues: direct physical contact, i.e. body surface to body surface, like that experienced in influenza or chlamydia infection; indirect (also called "fomite") contact, wherein contaminated articles are the medium by which infection is spread to susceptible persons, as in the spread of meningococcal meningitis by contact with contaminated utensils; and droplet contact, wherein relatively large (typically greater than 5 micrometers) droplets of respiratory fluid are exchanged via sneezing and coughing, as in the spread of the common cold.

Non-contact, or indirect, transmission can be subdivided into three types: "airborne", in which droplets of respiratory fluids less than 5 micrometers in size are spread by ventilation systems, as in the spread of Tuberculosis; "vehicle" transmission, in which a single contaminated source spreads the infection, as in a sick chef who spreads his illness via his food preparations; and "vector" transmission, which relies upon another organism, such as a mosquito, to spread the disease.

Each of these scenarios is nightmarish in the context of an extraterrestrial pathogen. If a prion is the expected culprit, then ingestion of some kind would be required, as the affected protein must be in close proximity with the proteins of the affected person. While terrifying, a prion epidemic might just be the most easily controlled, since the most important behavior for public health to control is ingestion.

Prions can enter a host's body mainly through ingestion, not just by eating, but also by the receipt of injections of protein-containing compounds. In theory, the receipt of any blood products represents an avenue for prion entry. Additionally, spontaneous mutations of previously normal, endogenous proteins could result in a prion disease. How an extraterrestrial prion could encourage mutation of terrestrial protein is, of course, unknown, but its possibility should not be easily ignored.

Further characteristics to consider are the disease's incubation period, virulence, and whether there is a limited period of communicability. A high degree of pathogenicity –the degree to which a disease kills its host-- seems likely for an alien menace, since it would not have evolved alongside human beings, and thus would not be able to enact the nuance of preserving a human host while also preserving its lethal qualities. Another interpretation is that there would not have been enough time for the pathogen and human host to have co-evolved alongside one another, thus lessening the ability of the host to defend him or herself from infection for an appreciable amount of time.

So, given what we know of extremophile behavior in vacuum, and applying assumptions about the evolutionary experiences of pathogens that had to endure the harshness of outer space, it seems that an extraterrestrial infection would likely have some predictable characteristics. First, any pathogen that is comet- or meteor-bonded would not require a natural reservoir to sustain itself. This suggests a high pathogenicity, since it would not have evolved an overwhelming necessity to sustain its host.

Second, basic genetic incompatibilities between biospheres suggest a less than optimal ability of a pathogen to act virally to hijack a host's cellular mechanism to mass produce itself. One result might be a very lengthy latency period. Admittedly, this reasoning falters if in fact the confounding factor is simply insufficient time for the alien pathogen to co-evolve alongside its new human host.

Third, given that an alien pathogen would have evolved in an unearthly environment with strange atmosphere, gravity, temperature, and surface materials composition, its ability to sustain itself on Earth outside of a host might be limited. On the other hand, the fact that it survived for a journey of millions of kilometers while embedded in rock or ice suggests that its ability to thrive outside a host might be extraordinary, at least for those pathogens resembling viruses that require a host environment. A cometary pathogen is likely to be more water-reliant, whereas a meteoric pathogen would have been embedded in rock, perhaps in a pocket of gas or fluid. In the final analysis, it seems likely then that such pathogens could be transmitted indirectly, meaning that they would not require direct contact between the carrier and a susceptible person to enact an infection.

The mechanism of infectivity is difficult to surmise. Direct tissue invasion seems unlikely, given that such an attack is possible by many earthly pathogens in part because of millions of years of co-evolution. The release of a toxin would also seem unlikely, given that toxin effectiveness is often a function of genetic fit, thus also requiring millions of years of co-evolution. Therefore, it seems most likely that an immunogenic response would be our undoing. While not a strict certainty, our immune systems might respond to an alien germ as it would a strange inorganic interloper: an allergic reaction, possibly fatal.

Guessing the re-infectivity ability of an alien disease is difficult indeed. Earthly diseases with high re-infectivity potential are ones that mutate quickly or that are difficult for human immune systems to identify. If we assume that physical structures on the surface of the alien pathogen are sufficiently disease-like to resemble Earthly antigens, and thus can trigger an immune response, then re-infectivity is dependent upon the disease's rate of mutation, such that the immune system would be fooled upon its second exposure to the disease. So, will an alien disease be able to mutate quickly? Or at all?

Consider that an organism that survived the harsh vacuum of space would have been exposed to more mutagenic radiation than most creatures on Earth could survive. It would therefore have to be extremely robust to mutation. Thus, it is unlikely to mutate on Earth, and would therefore have very poor re-infectivity potential.

Given these assumptions, the most appropriate deterministic epidemiologic model is, in our opinion, S → E → I → S, with the greatest unknown being the duration of the "E" latency compartment. Mind you, this analysis only applies if the immediate host is a human being. Should an alien pathogen find more comfortable residence within a non-human host, then the effects might be ecological, with selected species detrimentally affected, or, worse, zoonotic. In a zoonosis scenario, the alien pathogen could find a terrestrial non-human genome and physiology more attuned to its needs, then slowly acquire terrestrial genetic information, much like how an avian influenza virus can acquire genetic content from a human host. The result would be a pathogen better attuned to our biosphere, and thus much more likely to eventually infect humans, with a much higher probability of high infectivity, high re-infectivity, and high lethality.

4. Conclusion

There is some evidence that genesis on Earth may have been initiated off-world, suggesting that our biosphere shares characteristics with supposed biospheres on other planets. Via the interplanetary transit system of meteoric and cometary impact, it would then be highly likely that incredibly robust alien microscopic extremophiles are arriving on our planet. The extent to which those organisms could infiltrate our ecology is, of course, uncertain. But those that do have the potential to trigger disease epidemics with unknown parameters.

However, given some reasonable assumptions about such selective extremophilic pathogens, existing epidemiologic models can be used to better understand how such a disease would spread through human populations. The S → E → I → S deterministic model seems the best candidate for understanding and predicting an alien epidemic, with particular emphasis on what we expect to be a lengthy latency period.

Glossary

Basic reproductive number: the average number of secondary infections given the introduction of a single infectious case in a completely susceptible population.
Extremophiles: a microorganism adapted to sustain life and thrive in conditions of extreme temperature, acidity, alkalinity, or chemical concentration.
Incubation period: time interval between the exposure to infectious agent and the first appearance of symptoms
Infectious period: time interval during which the infected host can transmit the infectious agent.
Latency period: time interval between the exposure to an infectious agent and its detection in the host.
Oort cloud: an immense spherical cloud of icy objects that surrounds our solar system
Panspermia: the theory that life is distributed throughout the universe in the form of mediums which harbor microorganisms, of which may propagate under suitable environmental conditions.
Pathogenicity: the ability of an infectious agent to cause pathology or disease

Prions: A proteinaceous infectious agent that is neither bacterial, nor fungal, nor viral and contains no genetic material.
Robustness: organisms exhibiting adaptations to tolerate large changes in variables such as temperature, water availability, salinity or food availability etc.
Tardigrade: commonly referred to as 'water-bear', a water-dwelling, eight-legged, micro-animal capable to withstand tremendous temperatures, radiation, pressure, and food/water scarcity.
Virulence: the degree of pathogenicity of an infectious agent. In other words, a pathogen's ability to invade the tissue of a host. An organism is defined as being pathogenic or not, and, depending upon conditions, may exhibit differing levels of virulence.
Zoonotic/zoonosis: any disease of animals communicable to humans under natural conditions.

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